Prospects and results from the PPS detector

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on behalf of the CMS Collaboration
The PPS project

Originally developed as a joint CMS-TOTEM project (CT-PPS)

Detectors located in pre-existing TOTEM horizontal roman pots + new dedicated ones along the LHC beam line, at ±~200 m from the CMS interaction point

• two tracking stations and one timing station per side

Detects intact protons emerging from the IP and driven by LHC magnets in proximity of the proton beam ⇒ detectors approaching the beam at ~1 mm

Designed to operate continuously at standard LHC running conditions
Main target of the PPS physics program is the study of Central Exclusive Production (CEP) processes, where both protons remain intact and get detected in the roman pots.

Electroweak physics ("γγ collider")
- dilepton/diboson production: γγ → W+W−, ℓ+ℓ− → search for anomalous quartic gauge couplings (AQGC)
- search for SM-forbidden couplings: γγγγ, ZZγγ

QCD ("gg collider")
- pQCD tests of exclusive production
- characterisation of gluon jets (small quark component)

Search for New Physics
- CEP of new resonances
- search for invisible decays
Events of interest characterised by distinct signature:

- two leading protons reconstructed on opposite sides of the IP;
- large rapidity gap between central system and leading protons (colour-singlet exchange);
- possibility to “close” the event by matching central system and leading protons kinematics

![Event signature diagram](image)
Proton kinematics

Proton kinematics defined by:

- four-momentum transfer squared, $t \equiv (p_f - p_i)^2$;
- fractional momentum loss, $\xi \equiv (|p_f| - |p_i|)/|p_i|$

Proton acceptance in the detectors depends on the machine optics parameters:

Leading terms for “standard” LHC optics:

- $x \approx D_x(\xi) \xi$
- $y \approx L_y(\xi) \theta_y^*$

“waist” in proton impact point distribution
Proton acceptance

Mass and rapidity of the central system related to the protons $\xi$:

- $M^2 X = s \xi_1 \xi_2$;
- $y = 1/2 \ln(\xi_1/\xi_2)$

⇒ powerful matching requirement

Proton acceptance depends on the machine optics (mainly $D_x$) and on minimum attainable distance of detectors from beam

In 2016, maximum acceptance (~30%) for $M_X \approx 750$ GeV
Data taking in 2016 and 2017

Start of CT-PPS data taking advanced to 2016:
- TOTEM silicon strip detectors used for tracking;
- diamond detectors (developed for TOTEM) in timing stations

~15 fb$^{-1}$ of data recorded with tracking roman pots inserted

2017: towards design detector configuration
- tracking: per each side, one station with silicon strips, one station with 3D silicon pixels;
- timing: per each side, one mixed diamond - silicon (UFSD) station

~40 fb$^{-1}$ of data recorded with roman pots inserted
Detectors

- Tracking: design configuration, all stations equipped with 3D silicon pixel detectors (2 per side)
- Timing: stations equipped with diamond and double-diamond detector layers (1 station per side)

Roman pots regularly inserted in LHC fills
- data taking time almost superimposed to that of CMS
  \[ \sim 58 \text{ fb}^{-1} \] of data recorded

LHC “dynamic” beam settings
- luminosity levelling through multi-step $\beta^*$ and crossing angle tuning
Tracking detectors

Silicon strips

- 10 planes per station of “edgeless” silicon strip detectors (5 ‘u’ + 5 ‘v’)
- pitch: 66 μm; track resolution: ~12 μm
- designed for low-luminosity running (TOTEM)

Silicon pixels

- 6 planes per station of “slim-edge” silicon pixel detectors with 3D technology (tilted by ~18°)
- pixel size: 100 μm × 150 μm; track resolution ~20 μm
- designed for high-luminosity running ⇒ multi-track capability
Timing detectors

TOF measurement to reduce background from pileup (uncorrelated proton tracks)

- Ideally, desired resolution $\sigma_t \approx 20$ ps $\Rightarrow \sigma_z \approx 4$ mm

Diamond sensors
- 4 planes (3 in 2017) of CVD diamond sensors
- macro-pixels of varying size
- single-plane resolution target: $\sim 80$ ps
- 2+2 double-diamond layers in 2018 (larger signal expected $\Rightarrow$ faster rise time)
- radiation hard

Ultra-Fast Silicon Detectors
- 1 plane (in 2017) of UFSD, based on LGAD technology
- single-plane resolution in test beam: $\sim 30$ ps
- R&D to improve radiation hardness

Common readout electronics
Central dilepton production

Search for a centrally produced pair of oppositely charged leptons with forward proton tag

- photon-photon fusion process, never observed before
- test of theoretically clean exclusive cross section
- benchmark for similar searches of centrally produced high mass objects (e.g. W+W−)

**Signal**

- central exclusive production: small cross section for CT-PPS central mass range ($m(\ell^+\ell^-) \approx 400$ GeV)
- single dissociation (SD): broader $\xi$ range

**Analysis performed on** 9.4 fb$^{-1}$ of data at 13 TeV collected in 2016 (only tracking)

**Background**

(in coincidence with unrelated proton from pileup or beam background)

- double dissociation (DD)
  - inclusive Drell-Yan processes: $pp \rightarrow \gamma^*Z^* \rightarrow \ell^+\ell^- + X$

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Event selection

Dilepton selection:

- Trigger: two muons (electrons) with $p_T > 38\ (33)\ GeV$
- Dilepton vertex consistent with primary interaction
- “Good” leptons with $p_T > 50\ GeV$ and opposite charge
- Combined selection on distance of closest track to vertex and acoplanarity $a = 1 - |\Delta \phi(l^+ l^-)|/\pi$
- $m(l^+ l^-) > 110\ GeV$

Matching of central and proton kinematics:

- at least one proton track
- $\xi$ from central system: $\xi(l^+ l^-) = \frac{1}{\sqrt{s}} \left[ p_T(l^+) e^{\pm \eta(l^+)} + p_T(l^-) e^{\pm \eta(l^-)} \right]$
  (exact for exclusive, mostly within resolution for single dissociation events)
- signal region defined by $\xi(l^+ l^-) - \xi(p)$ match within $2\sigma$
Background estimate

Background mostly due to Drell-Yan or double dissociation events with unrelated proton track from pileup or beam background

• mostly data-driven estimate

<table>
<thead>
<tr>
<th>Contribution</th>
<th>After preselection</th>
<th>After kinematic match</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drell-Yan</td>
<td>11.36 ± 0.18</td>
<td>1.38 ± 0.06</td>
</tr>
<tr>
<td>DD</td>
<td>1.17 ± 0.02</td>
<td>0.108 ± 0.005</td>
</tr>
<tr>
<td>Total</td>
<td>12.52 ± 0.18</td>
<td>1.49 ± 0.07</td>
</tr>
<tr>
<td>Muons Observed</td>
<td>17</td>
<td>12</td>
</tr>
</tbody>
</table>

⇒ 5.1 σ excess over background

• no events with matching protons in both arms

First observation of proton-tagged γγ collisions at the electroweak scale

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Kinematics of signal events

No exclusive production event (double proton tag) observed

- consistent with MC predictions

$\xi(\ell^+\ell^-)$ out of proton acceptance
Continuation of the PPS program has been approved for LHC Run 3 (2021-2023) at $\sqrt{s} = 14$ TeV

New detectors needed, to replace current ones damaged by radiation

**Tracking:** new 3D silicon pixel detectors
- technology very similar to existing one
- same geometry/granularity

**Timing:** double diamond sensors
- proposal to double the number of timing stations

**LHC luminosity levelling** pushed forward

$\Rightarrow$ nearly continuous variation of machine optics parameters: reconstruction will have to follow
Summary and plans

PPS has demonstrated the feasibility of studying forward proton-tagged events at high luminosity

First observation of central (semi)exclusive production of high mass lepton pairs

Total data sample of $\sim 110 \text{ fb}^{-1}$ collected in Run 2 (2016-2018)

Several analyses currently ongoing or starting

- central production of $\gamma\gamma$, WW, ZZ, $\gamma Z$, $t\bar{t}$
- missing mass searches

Improvements expected in the reconstruction of proton kinematics

Detector construction started for LHC Run 3 (2021-2023)

- goal: $\sim 300 \text{ fb}^{-1}$
Additional material
MX acceptance and resolution

In exclusive dijet production both protons escape intact the hard interaction, and a two-jet system is formed. Figure 17 shows the mass acceptance as a function of the centrally produced mass for exclusive dijet events produced in pp collisions.

The estimated resolution is shown for tracking detectors located at a distance of 20 mm from the beam center. Figure 18 illustrates the mass resolution as a function of the mass for different detector geometries.

Here, we consider two physics cases that address different issues: exclusive dijet and exclusive WW production. These processes will allow us to investigate central exclusive production with both protons and electrons.

Study of physics processes with forward protons may extend the physics reach of the LHC experiments.

The occupancy and performance of the time-of-flight detectors are studied for different detector geometries. Here again, an average of 50 pileup interactions mixed with the primary interaction is assumed.

Segmentation of the timing detector active area is considered for both the baseline option of the QUAR-TIC detectors, and for the study-option of solid state finely-segmented "diamond-like" detectors discussed in detail in Section 5.2.5.

Alignment of the CDF RP Spectrometer is achieved by seeking the maximum of the occupancy distributions (at the 0.5x0.5x0.5 cm3 level) and less than 100% acceptance when pileup and beam-related backgrounds are considered.

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Detector alignment

Procedure developed and used extensively by TOTEM

Dedicated alignment fills (low luminosity)
- once per beam optics setting
  1. detector approach to the edge of the scraped beam;
  2. local alignment with overlapping vertical-horizontal detectors (minimise residuals)
  3. alignment with respect to the beam from hit occupancy distributions

Physics fills
- each fill
  - match $x$ distribution with distribution from alignment fill

Finally, the alignment of CT–PPS with respect to the beam is performed, again with data from the dedicated fill. A sample of several thousand elastic scattering events, $pp \rightarrow pp$, is used for that purpose. The LHC optics causes the elastic hit distribution in any vertical RP to have an elliptical shape centered on the beam position. This symmetry is exploited to determine the position of the RP with respect to the beam.

The uncertainties in the results of the procedure just discussed are $5 \text{ mrad}$ for rotations, $50 \mu\text{m}$ for horizontal shifts, and $75 \mu\text{m}$ for vertical shifts.

3.2 Physics fills

Since the RPs move, and the beam position can change, the position of CT–PPS with respect to the beam needs to be redetermined for each fill. The physics fills are characterized by high intensity with only the horizontal RPs inserted at much larger distances (about $15 \text{ s}$) from the beam than in the alignment fill, and therefore a different procedure is employed.

The horizontal alignment is based on the assumption that the scattered protons from a $pp$ collision at the IP have the same kinematic distributions in all fills. Given the stability of the LHC conditions (RP positions, collimator setting, magnet currents, and beam orbit), this leads to the spatial distributions of the track impact points observed in the RPs (Section 4.2). The alignment is then achieved by matching these distributions from a physics fill to those from the alignment fill. An example of this procedure is shown in Fig. 4. For this method to work, it is important to suppress the background due to secondary interactions taking place between the IP and the RPs. To this end, the correlation between the coordinates of the horizontal hit positions in the near and far RPs is used. The total uncertainty of the horizontal alignment is about $150 \mu\text{m}$.

Figure 4: Distribution of the track impact points as a function of the horizontal coordinate for the alignment fill (black points), a physics fill before alignment (blue points), and after alignment (red points). The beam center is at $x = 0$ for the black and red points; the $x$ axis origin is undefined for the blue points. In the alignment procedure the overall normalization of the histogram is irrelevant; the histograms from different fills are therefore rescaled to compare their shapes.
Tracking detector hit maps

Alignment run, May 2017

Sector 45

Sector 56

Top

Bottom

Horizontal

y (mm)

x (mm)

x-y coordinates relative to an arbitrary system of reference

Data collected during alignment run in end of May 2017

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6.2 Matching central and proton variables

Events with at least one well-reconstructed proton track in CT-PPS are retained for further analysis. For each event, the value of the fractional momentum loss of the scattered proton is simulated in Fig. 10; in this case only one of the two possible solutions correspond to the protons moving in the direction.

The formula is exact for exclusive events, but holds also for the single-dissociation case, as illustrated where the two solutions for...